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The Main Factors Affecting Heat Transfer Along Dense Phase CO_2 Pipelines

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ABSTRACT

Carbon Capture and Storage (CCS) schemes will necessarily involve the transportation of large volumes of carbon dioxide (CO_2) from the capture source of the CO_2 to the storage or utilisation site. It is likely that the majority of the onshore transportation of CO_2 will be through buried pipelines. Although onshore CO_2 pipelines have been operational in the United States of America for over 40 years, the design of CO_2 pipelines for CCS systems still presents some challenges when compared with the design of natural gas pipelines. The aim of this paper is to investigate the phenomenon of heat transfer from a buried CO_2 pipeline to the surrounding soil and to identify the key parameters that influence the resultant soil temperature. It is demonstrated that, unlike natural gas pipelines, the CO_2 in the pipeline retains its heat for longer distances resulting in the potential to increase the ambient soil temperature and influence environmental factors such as crop germination and water content. The parameters that have the greatest effect on heat transfer are shown to be the inlet temperature and flow rate, *i.e.* pipeline design parameters which can be dictated by the capture plant and pipeline's design and operation rather than environmental parameters. Consequently, by carefully controlling the design parameters of the pipeline it is possible to control the heat transfer to the soil and the temperature drop along the pipeline.

KEYWORDS

CO_2 pipelines, temperature profile, sensitivity analysis, heat transfer, soil temperature, hydraulic modelling, CCS

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1. INTRODUCTION

Carbon Capture and Storage (CCS) is one method of reducing carbon dioxide (CO_2) emissions into the atmosphere which would otherwise contribute towards global climate change. CCS involves capturing CO_2 from a large industrial point source (such as a power station) and transporting the CO_2 for either usage (for example for Enhanced Oil Recovery (EOR)) or for permanent storage in a

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geological site. Depending on the distance and availability of a suitable storage site, the transportation of the CO_2 to the storage site is by means of a pipeline network, by ship based transportation or a combination of both.

For the onshore pipeline transportation of CO_2, after compression at the capture plant, the CO_2 streams will typically be at temperatures between 30°C to 50°C and pressures between 10MPa to 20 MPa (Farris, 1983; Race et al., 2012) putting the CO_2 streams in either supercritical or dense phase. For CO_2 pipelines, it is important to understand how the temperature of the fluid varies along the pipeline, as the temperature determines the phase of the fluid and affects density, pressure drop (Dongjie et al., 2012) and economics (Teh et al., 2015; Zhang et al., 2006). Colder ground conditions provide greater cooling of the CO_2 stream and, as a result, lower inlet pressures are required to keep the CO_2 in a liquid phase. In addition, higher densities are maintained at lower temperatures, which is more efficient for pipeline transportation and better for pump operation.

When the fluid temperature is higher than that of the surrounding soil, due to the temperature difference between the CO_2 and surroundings and elevation changes along the pipeline route, there will be heat exchange between the CO_2 stream and the surrounding environment with the temperature of the fluid getting closer to (but not necessarily reaching) ambient temperature along the length of the pipeline. The heat transfer between the fluid and the surrounding soil takes place in 4 stages: firstly there is forced convection from the film of fluid coating the inner surface of the pipeline, the second stage of heat transfer is conduction through the pipe wall, heat transfer then proceeds via conduction from the outer surface of the pipeline and through the surrounding soil. Finally there is natural convection from the surface of the soil to the surrounding air. In the conduction stages through the pipeline and from the pipeline to the soil, it is possible to include the effects of any pipeline coatings (which may be included on the pipe internal surface, for example to, facilitate flow) and insulation on the outside of the pipe. In this work coatings are neglected due to a lack of publically available information on their heat transfer properties and no insulation is added to the pipeline following the planned demonstration projects in the UK (Capture Power, 2016).

In natural gas pipelines the fluid generally reaches ambient temperature very rapidly but in CO_2 pipelines this process can be much slower. Heat transfer from the fluid to the surroundings can cause environmental issues. For example, pipelines carrying warm fluid can cause heating of the surrounding soil, which may result in premature crop growth and affect soil moisture and the temperature along the pipeline Right of Way (ROW) (Dunn et al., 2008; Naeth et al., 1993; Neilsen et al., 1990) in some circumstances. In order for a pipeline operator to be able to manage these effects, it is important to understand the degree of influence that operational and environmental factors have on heat flux from the fluid to the surrounding soil. Factors influencing the degree of heat flux from a buried pipeline include the fluid pressure and temperature, the soil temperature, the soil type and moisture content (Becker et al., 1992), the thermal conductivity of the pipeline steel and the elevation profile along the pipeline route (Teh et al., 2015). Some parameters such as the temperature of the fluid, operating pressure and initial temperature of the CO_2 can be controlled at the capture plant. Other parameters, such as the soil type and ambient temperature are out of the control of the pipeline operator.

1.1. Heat transfer from CO_2 pipelines

There is very little publically available work on heat transfer from CO_2 pipelines. The heat transfer characteristics of CO_2 pipelines surrounded by water were analysed experimentally and computationally by Drescher et al. (2013). They found that the water temperature has a high impact on the amount of heat transfer and a range of values for the overall heat transfer coefficient for a CO_2 pipelines surrounded by water, finding a mean value of 44.7W/m^{2}K. The importance to CO_2 pipeline operation of the soil temperature and type, thermal conductivity of the pipeline and topography of the pipeline route was highlighted in Dongjie et al. (2012) and Teh et al. (2015). They found that transporting and storing liquid CO_2 can be cheaper than supercrtical CO_2, that cooler ground conditions can lead to cost savings and highlighted the need for futher work to explore the effect of burial depth and of soil thermal conductivity. The effect of pipeline operating temperature on UK soils was investigated in Lake et al. (2016) who provided the first set of empirical data on soil temperature and moisture profiles for CCS pipelines. There is still need for further work on how best to operate a CO_2 pipeline with regards to heat transfer and experimental work into heat transfer from full scale CO_2 pipelines. This work is a step towards the former.

Through pipeline simulations and a sensitivity analysis this study identifies the dominant parameters affecting heat transfer from liquid CO_2 pipelines and discusses how an operator can control heat transfer out of the pipeline to minimise the impact of heat transfer. Firstly a preliminary study was conducted consisting of a series of eight steady-state pipeline simulations. This allowed an investigation of the influence of ground temperature, flow rate, inlet temperature, burial depth, soil conductivity, inlet pressure and CO_2 composition on the rate of temperature loss along the pipeline and a comparison to previous results. A sensitivity analysis, using a Gaussian emulator, was then performed to identify which of the parameters investigated in the preliminary analysis had the strongest influence on the temperature drop along the pipeline. The Gaussian emulation approach is highly computationally efficient (far fewer model runs are required compared with, for example, Monte-Carlo based methods), it allows for a complete range of sensitivity measures to be computed from one set of pipeline simulation results and statistical performance is included in the process. It is applicable to the current study because the data from the pipeline simulations is smooth (*i.e.* there are no sudden jumps when moving between data points). Smoothness was ensured by keeping the pipeline simulations in the dense or supercritical phase.

2. HYDRAULIC MODELLING OF THE CO_2 PIPELINES

2.1. Model setup

The modelling approach that was adopted for this study is described in detail in (Wetenhall et al., 2014). Heat transfer modelling details are given in Section 2.2 while the other details are presented in summary. PIPESIM, a steady-state flow simulator (Schlumberger, 2010), was used to conduct the hydraulic modelling of the CO_2 pipeline. As implemented in the software package MultiFlash (Infochem, 2011), the fluid physical (density, enthalpy, compressibility and heat capacity) and phase properties were determined using the Peng-Robinson Equation of State (Peng and Robinson, 1976), fluid viscosity was calculated using the Pedersen model (Pedersen et al., 1984) and SUPERTRAPP (NIST, 2007) was used to determine fluid thermal conductivity. Figure 1 shows a flow diagram for the pipeline simulation procedure as implemented in PIPESIM. The procedure requires the simultaneous solution of the conservation of mass, momentum and energy equations. From the solution of these equations, the pressure and temperature drops along the length of the pipeline can be calculated given two of the parameters of initial pressure, final pressure or flow rate. It is recognised that the Pedersen model was developed for oil applications but it has been shown to provide a conservative prediction for the hydraulic modelling of CO_2 streams in the absence of a CO_2 viscosity model (Wetenhall et al., 2014). The flow equation selected for this analysis was the Beggs and Brill correlation (Beggs and Brill, 1973) with the Moody friction factor (Moody, 1944) as defined in Brill and Mukherjee (1999).

2.2. Modelling the heat transfer from the fluid to the surrounding soil

To calculate the rate of heat transfer from the fluid contained inside the pipeline to the surrounding soil, the pipeline is first divided into segments. The maximum segment length was set to 0.05m, as it was found that the results were not sensitive to smaller segmentation lengths. For each segment, a heat transfer balance is performed using the First Law of Thermodynamics, *i.e.* the total amount of energy entering the pipeline segment must equal the amount of energy leaving the segment plus the energy transferred to or from the surroundings. The hydraulic modelling procedure couples the change in fluid properties with the heat and work done to the fluid through the pipeline segment.

For steady state flow, the First Law of Thermodynamics for a pipeline segment may be written as (Mohitpour et al., 2003):

$$\Delta\left\{\left(H+\frac{1}{2}v_m^2+gz\right)dm\right\}=\Sigma\delta Q-\delta W \tag{1}$$

where the first three terms on the left hand side of the equation represent the changes in enthalpy, kinetic and gravitational potential energy respectively; v_m is the mean velocity of the fluid being transported in the pipeline, g is the gravitational constant, z is elevation, δQ is the amount of heat energy transferred to or from the pipeline segment and δW is the work done to the fluid. For steady state heat transfer caused by a difference between two temperatures, in this case the fluid (T_f) and the surrounding soil (T_g), the total amount of heat transferred through a pipeline segment may be written in terms of a conduction shape factor, *S*, which is defined by:

$$Q = 2\pi k_g S \Delta T \tag{2}$$

where k_g is the thermal conductivity of the soil, ΔT is the temperature difference between the fluid and soil, Q is the amount of heat energy transferred and *S* depends on the geometry of the system (some examples of *S* are listed in Kreith and Bohn (2001).

For a buried pipeline, a solution for the conduction shape factor with convective boundary conditions for the interfaces between the pipeline and fluid film and between the ground and ambient air is facilitated by the use of bipolar cylindrical coordinates: (α, τ, z). If z is set to the pipeline burial depth measured to the centre of the pipeline, Z, and D_o is the outside diameter then the lines $\alpha = 0$ and $a = \alpha_o = \cosh^{-1}\frac{2Z}{D_o}$ of the pipeline represent the ground surface and outer pipeline wall respectively (which are where the convective boundary conditions are applied). A solution, which closely agrees to numerical solutions in the literature, can then be found (Ovuworie, 2010):

$$S = \frac{Bi_p a_{bur}}{\sqrt{\left(cosh\alpha_o - Bi_p a_{bur}\alpha_o + \frac{Bi_p}{Bi_g}\right)^2 - \left(1 + \frac{Bi_{ip}}{Bi_g}\right)^2}} \tag{3}$$

where

$$\alpha_o = -\cosh^{-1}\frac{2Z}{D_o} \tag{4}$$

$$a_{bur} = 4\frac{Z^2}{D_o^2} - 1 \tag{5}$$

k_g is the thermal conductivity of the soil and Bi_p and Bi_g are the Biot numbers of the pipeline and ground given by:

$$Bi_p = \frac{U_{pipe} D_o}{2k_g} \tag{6}$$

$$Bi_g = \frac{h_a D_o}{2k_g} \tag{7}$$

Here, h_a is the heat transfer coefficient of the fluid film of ambient air at the ground surface and the overall heat transfer coefficient of the pipeline, U_{pipe}, is a combination of the heat transfer coefficients of the fluid film, h_{film}, and pipeline, h_{pipe}:

$$\frac{1}{U_{pipe}} = \frac{1}{h_{film}} + \frac{1}{h_{pipe}} \tag{8}$$

The heat transfer coefficients of the pipeline and the films of fluid between the pipeline and internal fluid and the ambient air and soil can be determined by considering the layers between the fluid and pipeline wall (convective) and radially outwards through the pipeline wall (conductive) separately.

2.2.1.Heat transfer between the ambient air and surface of the soil

Heat transfer from the surface of the soil to the film of ambient air at the surface is convective and the corresponding heat transfer coefficient may be split into a free convection component, h_{free}, (capturing the density differences) and a forced convection component, h_{forced}, (capturing the effect of the wind):

$$h_a = h_{forced} + h_{free} \tag{9}$$

As the wind speed is below 0.5m/s close to the soil surface, the free convection component dominates so a limiting value of 4W/m^{2}K was used for h_a (Schlumberger, 2010).

2.2.2. Heat transfer between the fluid film and pipeline wall

Heat transfer from the film of fluid at the surface of the pipeline to the inner pipeline wall is convective and the heat transfer coefficient for this layer may be expressed as:

$$h_{film} = \frac{k_f Nu}{D_i} \tag{10}$$

where k_f is the thermal conductivity of the fluid (calculated using SUPERTRAPP (NIST, 2007)), Nu is the Nusselt number and D_i is the pipeline inner diameter. For the flow conditions considered in this study, the flow regime is always seen to be turbulent (with Reynold's numbers of the order 10^6), and therefore, for the Nusselt number, semi-empirical correlations of the Reynold's number and Prandtl number can be used (Kreith and Bohn, 2001):

$$Nu = 0.023 Re^{0.8} Pr^{0.33} \left\{1 + \left(\frac{D_i}{\delta L}\right)\right\} \tag{11}$$

where δL is the pipeline segment length and

$$R_e = \frac{\rho v_m D_i}{\mu} \tag{12}$$

$$Pr = \frac{\mu \, c_p}{k} \tag{13}$$

where μ is the viscosity and ρ is the density of the fluid.

2.2.3. Heat transfer through the pipeline wall

Heat is transferred through the pipeline by conduction. Applying Fourier's Law of Conduction to a pipeline of homogenous material, it can be shown (Kreith and Bohn, 2001) that the heat transfer coefficient through the pipeline wall (h_{pipe}) is given by:

$$\frac{1}{h_{pipe}} = \frac{D_o}{k_{pipe}} \ln \frac{D_o}{D_i} \tag{14}$$

where k_{pipe} is the thermal conductivity of the pipeline material. Equations (10) and (14) can then be used in Equation (8) to give the heat transfer coefficient of the pipeline.

2.2.4. Heat transfer from the fluid to the surrounding soil

Once the heat transfer coefficient of the pipeline has been calculated, using the procedure in Section 2.2.3, Equations (2) and (3) can be combined to give the overall heat transferred to or from the fluid to the surrounding soil. Equation (1) can then be used to perform an energy balance through the pipeline segment and therefore determine the temperature of the CO_2 stream as part of the steady-state hydraulic modelling process.

3. PRELIMINARY STUDY

A series of eight steady-state pipeline simulations was conducted as part of a preliminary study to compare the model with previous results and investigate the influence of ground temperature, flow rate, inlet temperature, burial depth (measured to the top of the pipeline), soil conductivity, inlet pressure and CO_2 composition on the rate of temperature loss along the pipeline. Firstly a base case study was established against which other scenarios could be compared. The specification of the pipeline section used in the base case is presented in Table 1. The pipeline operating conditions are assumed to be typical of the requirements of a pipeline designed to be part of an anchor project supporting a CCS network. The flow rate was selected based on the White Rose project (AECOM, 2013). The operating pressure of 150barg has been selected to ensure that the CO_2 remains in the dense phase along the pipeline length. It has been assumed that the manufacture and construction standards and practices for CO_2 pipelines will be similar to those used for natural gas pipelines and therefore no insulation has been applied to the pipelines in the hydraulic model and the pipes have been buried to a depth of 1.2m as measured from the top of the pipeline. This figure is considered to be representative of the maximum depth of cover required for the construction of onshore pipelines in the UK (PD8010-1, 2015). A roughness value of 0.0457mm has been used as the recommended value for commercial steel pipelines (Mohitpour et al., 2003). The soil thermal conductivity is considered to be constant along the length of the pipeline and has been taken to be 0.87W/mK, which is typical of a moist sandy or clay type soil (McAllister, 2005). The ambient ground temperature has been set at 3°C for the base case representing a winter scenario in the UK.

Having established this base case pipeline, seven cases were run to investigate the influence of ground temperature, flow rate, inlet temperature, burial depth, soil conductivity, inlet pressure and CO_2 composition on the rate of temperature and pressure loss along the pipeline. The parameters that were changed for each study from the base case are detailed in Table 2. Of particular note is the approach taken to investigate the effect of composition. Previous work indicates that the influence of a particular component in hydraulic analysis is highly influenced by the critical temperature and pressure of the component or impurity relative to pure CO_2 (Race et al., 2012; Wetenhall et al., 2014). In this respect, the two impurities that could be present from power plant capture plant, which have the most divergent effects on hydraulic behaviour are sulphur dioxide (SO_2) and hydrogen (H_2). As a result only these two components have been selected to represent a best and worst case.

3.1. Preliminary study results

For each case listed in Table 2, the pressure and temperature profiles along the 150km long pipeline were determined. The results were then presented in terms of the pressure drop/km (barg/km) or temperature drop/km (°C/km) and are shown in Figure 2 and Figure 3. The pressure and temperature drops per km obtained in this study are in line with the current literature (Teh et al., 2015; Zhang et al., 2006~~)~~). In particular, (Teh et al., 2015) reports temperature drops of 0.04 to 0.05°C/km for scenarios with similarity to Case 1.1 and (Zhang et al., 2006) reports pressure drops of 0.02 to 0.03bara/km for scenarios with similarity to Cases 1.1 and 3.1.

The maximum pressure drop observed was 0.05barg/km for Case 2.1, the scenario with a flow rate of 17MT/year and a ground temperature of 3°C. This is below pressure gradients quoted in the literature for CO_2 pipelines which are around 0.2bar/km (Seevam et al., 2010; Vandeginste and Piessens, 2008). It is therefore concluded that the pressure drop is not significantly affected by the input parameters.

In terms of temperature drop, the temperature of the fluid does not reach the temperature of the surrounding soil along the length of the pipeline. A review of the temperature profiles in Figure 3 indicates that the inlet temperature, flow rate, burial depth and soil conductivity appear to have the largest effects on temperature drop. Parameters which seem to have a lesser effect are ground temperature and composition. However, it is recognised that these conclusions are drawn from a small sample set and the interactions between parameters have not been studied in detail in this preliminary analysis.

4. SENSITIVITY ANALYSIS

The next stage in the analysis was to conduct a sensitivity analysis using a Gaussian emulator approach to identify which of the parameters investigated in the preliminary analysis had the strongest influence on the temperature drop along the pipeline. The rationale behind this analysis was to determine the operational parameters that could or should be controlled by a pipeline operator to maximise temperature drop or whether the critical parameters were environmental in nature and therefore more difficult or impossible to control.

4.1. Gaussian emulator approach

The technique that has been used for the sensitivity analysis is the Gaussian emulator approach using the Gaussian Emulation Machine for Sensitivity Analysis (GEM-SA) software (GEM-SA, 2013) which provides a statistical approximation with which it is possible to perform a sensitivity analysis.

In order to perform an accurate sensitivity analysis on a model with a number of interrelated inputs (in this case ground temperature, flow rate, inlet temperature, burial depth, soil conductivity and inlet pressure) and outputs (temperature drop), a large number of simulation model runs is required. Running this number of models in PIPESIM is prohibitive in terms of time and computer resource requirements. A Gaussian emulator takes a series of inputs and the corresponding series of outputs from running the simulation model (PIPESIM) and creates an emulator of the simulator, from which predictive runs can be made quickly and cheaply in terms of computer processing requirements. The Gaussian emulator also gives a probability distribution to show how the simulator performs away from the design points. If the emulator is able to approximate the results of the simulator accurately, then a sensitivity analysis of the model using the emulator is an accurate approximation to the sensitivity analysis of the simulator.

4.2. Input for the Gaussian emulator

The range of input data that was used for the Gaussian Emulator is shown in Table 3. The ranges were selected such that operation is maintained at pressures above the bubble point curve in order to avoid two-phase flow. For the sensitivity analysis, two simulations were conducted; one for the 914.4mm Outside Diameter (OD) pipeline as specified in Table 1 and the other for a 610mm OD, 19.1mm wall thickness pipeline. A 610mm OD pipeline was selected as this was the size of the pipeline proposed for the White Rose project (AECOM, 2013), an example of a CO_2 pipeline designed to facilitate development of a pipeline transportation network. The length of the 610mm OD pipeline and the pipe roughness used in the simulation remained the same as detailed in Table 1.

A series of 200 datasets of training inputs for the Gaussian Emulator were generated using a maximin Latin hypercube design[1]. This ensures that a good sample set of inputs was selected with which to build the emulator that covers the whole parameter set range. The range is shown in Table 3. Each of the 200 datasets was run in PIPESIM to obtain the training outputs. The emulator was then built using the GEM-SA approach (O'Hagan, 2004).

The emulator provides a statistical approximation indicating the likelihood that the predicted value is the true output of the model, *i.e.* in this case the PIPESIM output. At the training points, the uncertainty of not emulating the simulated value is zero; away from the training outputs the distribution associated with the inputs gives a mean value for the output for a Gaussian process of uncertainty around the mean, each of the six input variables having a normal distribution.

4.3. Gaussian emulator results

The Gaussian emulators provided a good predictor for the output from PIPESIM. The variance of expected code outputs for the 914.4mm and 610mm OD pipelines were 0.003 and 0.005 respectively. Furthermore, predictions of the emulators were made for five sets of randomly selected model inputs and compared with the corresponding output from PIPESIM. Considering the difference between the predictions and PIPESIM output both emulators had R^2values of 1.00.

The results of the GEM-SA emulations for the 914.4mm and 610mm OD pipelines, using the input parameter ranges given in Table 3 are plotted in Figure 4 and Figure 5 respectively. The magnitude of the effect on the y-axis of each graph indicates the expected value of the temperature decrease of the fluid obtained by averaging over all other inputs. Negative slopes on the graphs indicate that the effect on heat transfer from the fluid to the soil decreases with increasing values of the input parameter, *i.e.* the outlet temperature of the fluid will be higher with increasing values of the input parameter. Similarly, a positive slope indicates that the effect on temperature decrease of the fluid increases with increasing values of the input parameter, *i.e.* the outlet temperature of the fluid is lower with increasing values of the input parameter. The plots also indicate the uncertainty in the emulated results with the wider bands indicating more uncertain regions of the emulation. Full details of the theory behind the sensitivity analysis are provided in Oakley and O’Hagan, 2004).

[1] Latin hypercube sampling is a statistical methodology for generating a sample of parameter values from a multi-dimensional distribution. The sampled variables are then randomly combined into plausible variable sets for one calculation of the output function (in this case outlet temperature).

It is noted that the effect of the input variables on the temperature loss show the same qualitative behaviour between the two pipeline diameters. However, the magnitudes of the effects are slightly different for each case as a change in pipeline diameter results in a change in the pressure gradient along the pipeline and therefore the results cannot be compared quantitatively.

4.3.1. Effect of input variables

Figure 4a and Figure 5a illustrate the effect of varying inlet pressure on the outlet temperature. Over the range of pressures investigated, it can be seen that changing the inlet pressure has very little effect on the outlet temperature of the fluid, provided that the inlet pressure is high enough to avoid two phase flow along the entire pipeline length. The input parameters were specifically selected for the GEMS emulations to avoid two-phase flow.

The effect of varying inlet temperature of the fluid is shown in Figure 4b and Figure 5b and follows a linear trend as you would expect from looking at Equation (2). With increasing inlet temperatures, the heat transfer from the fluid to the soil is increased and therefore the outlet temperature of the fluid is decreased. However, increasing the ground temperature has a linearly decreasing effect on heat transfer from the fluid (Figure 4d and Figure 5d), *i.e.* increasing the ground temperature decreases the effect on the outlet temperature of the fluid. The same trend is shown for increasing burial depth (Figure 4e and Figure 5e) although the effect tends to an asymptotic value; indicating that above about 1m, the burial depth has little effect on the outlet temperature of the fluid.

Soil conductivity also shows asymptotic rather than a linear behaviour with higher soil conductivities increasing the amount of heat transfer from the fluid and decreasing its outlet temperature (see Figure 4c and Figure 5c). However the effect is less marked above a soil conductivity of about 2.5W/mK.

As the graphs of Figure 4f and Figure 5f illustrate, flow rate has a significant effect on outlet temperature. As the flow rate increases less heat is transferred from the fluid to the surrounding soil and therefore the fluid outlet temperature is increased. Smaller flow rates will lead to lower fluid velocities and thus increased heat transfer. However, it can be seen that the largest effects occur at lower flow rates with asymptotic behaviour observed at higher flow rates. For example, for the 914.4mm OD pipeline, increasing the flow rate above 600kg/s will have a marginal effect on the outlet temperature for the simulations conducted**.**

At high flow rates, the pressure drops more rapidly along the pipeline than at lower flow rates. Consequently, the density of the fluid decreases along the pipeline and the velocity and the Reynolds Number (R_e) increases. Most of the heat loss in turbulent flow is convective, as opposed to conductive, and an increase in velocity causes an increase in turbulence and an increase in convective heat transfer. At lower flow rates the density increases along the pipeline, the flow velocity decreases and the convective heat transfer decreases.

However, the density of the fluid also affects the thermal conductivity of the fluid (Polyakov, 1991). As the density increases in the pipeline operating region, the thermal conductivity of CO_2 increases and the rate of heat transfer increases. These competing phenomena could account for the asymptotic shape of the flow rate curve in Figure 4f and Figure 5f.

4.3.2. Sensitivity Analysis Results

As well as allowing the effect of each variable to be considered in turn (as demonstrated in Figure 4 and Figure 5), the GEM-SA analysis also allows the relative sensitivity of each variable and the interaction between variables to be studied. Table 4 shows the total effect of each input and the contribution to the total variance of each input (*i.e.* the scatter about the mean) for the range of variables considered in Table 3. From this table it can be seen that inlet temperature and flow rate (shaded in Table 4) have a much larger effect on outlet temperature than inlet pressure, ground temperature, soil conductivity and burial depth. It is highlighted that the effect of flow rate is higher for the larger diameter pipeline and the effect of inlet temperature is greater for the smaller diameter pipeline.

The interaction effects between each pair of variables for the two diameters of pipeline are displayed in Table 5 in terms of their contribution to the total variance. This analysis indicates that, for the range of input values considered, the interaction between inlet temperature and flow rate has the greatest effect for both of the pipelines considered. No higher orders were considered as the main and joint effects account for 98% of the total variance.

5. CONCLUSIONS

As a result of the analysis conducted, it has been shown that the inlet temperature and flow rate have the largest effect on temperature gradient for the two diameters of pipeline considered in this study.

The heat loss from the pipeline is dominated by the density of the CO_2 which in turn is affected by the pressure and temperature drop along the pipeline. As a result, the relationship between outlet temperature and flow rate has been shown to be highly non-linear.

In natural gas pipelines the internal fluid rapidly reaches ambient temperature (Deaton, 1941). However, as shown in this study and in the literature, in dense or supercritical phase CO_2 pipelines the rate of heat transfer can be slow. This can lead to potential problems, for instance, if the fluid is ‘shut in’ the pipeline for a period of time, then, since the fluid temperature has remained high, there will be a quantity of heat energy transferred to the surroundings and the temperature of the surrounding soil will be increased. The slow rate of heat loss also affects CO_2 pipeline transportation performance as the CO_2 streams have higher density at lower temperatures.

Although environmental factors, such as ground temperature and soil conductivity, have a marginal effect on temperature loss, this effect is weaker than the parameters which are controlled by the pipeline design such as inlet temperature and flow rate. It can therefore be concluded that the temperature loss along a pipeline is predominantly controlled by the design of the pipeline which can in turn be dictated by the capture plant's design and operation. Consequently, the operating parameters need to be selected very carefully, especially the flow rate, to control the temperature loss along the pipeline. In future work it would be useful to explore the effect that greater cooling at the capture plant has on the costs of transportation.

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TABLES

Pipeline parameters		*Unit*
Outside diameter (OD)	914.4	mm
Wall thickness	25.4	mm
Pipeline length	150	km
Pipe roughness	0.0457	mm
Operating conditions		
Inlet pressure	150	barg
Inlet temperature	40	ºC
Flow rate (CO_2)	12	Mt/year
Environmental conditions		
Ground temperature	3	ºC
Composition of CO_2	100% CO_2	
Burial depth	1.2	m
Soil conductivity	0.87	W/mK
Elevation profile	Flat	

Table 1: Input parameters for base case pipeline

Scenario 1: Effect of ground temperature		Ground temperature (ºC)
	Case 1.1	14
	Case 1.2	5
	Case 1.3	3
Scenario 2: Effect of flow rate		**Flow rate (MT/yr)**
	Case 2.1	17
	Case 2.2	5
Scenario 3: Effect of inlet temperature		**Inlet temperature (ºC)**
	Case 3.1	50
	Case 3.2	30
	Case 3.3	20
Scenario 4: Effect of burial depth		**Burial depth (m)**
	Case 4.1	0
	Case 4.2	2
Scenario 5: Effect of soil conductivity		**Soil conductivity (W/m.k)**
	Case 5.1	0.15
	Case 5.2	2
	Case 5.3	4
Scenario 6: Effect of inlet pressure		**Inlet pressure (barg)**
	Case 6.1	120
	Case 6.2	100
Scenario 7: Effect of fluid composition		**Composition (wt%)**
	Case 7.1	CO_2 + 5% H_2
	Case 7.2	CO_2 + 5% SO_2

Table 2: Case studies used in the preliminary study

Parameter	Range for 914.4mm OD Pipe	Range for 610mm OD Pipe
Inlet pressure (barg)	120 - 200	130 - 200
Inlet temperature (ºC)	20 - 50	20 - 50
Ground temperature (ºC)	0 - 15	0 - 15
Flow rate (kg/s)	15 - 1100	15 - 400
Soil conductivity (W/m.K)	0.1 - 4	0.1 - 4
Burial depth (m)	0 - 2	0 - 2

Table 3: Input parameters for GEMS emulations

Input Variable	Variance (%)	Total Effect	Variance (%)	Total Effect
	914.4mm OD Pipeline		610mm OD Pipeline	
Inlet Pressure (x1)	0.06	0.24	0.05	0.22
Inlet Temperature (x2)	23.33	30.50	39.11	45.05
Ground Temperature (x3)	6.10	9.28	9.45	12.28
Flow Rate (x4)	50.63	59.54	30.42	37.29
Soil Conductivity (x5)	5.48	8.82	9.38	13.82
Burial Depth (x6)	2.83	5.80	1.64	4.24

Table 4: Sensitivity analysis results for the 914.4mm and 610mm diameter pipelines

Joint Effect	Variance (%)	Joint Effect	Variance (%)
914.4mm OD Pipeline		**610mm OD Pipeline**	
x1.x2	0.01	x1.x2	0.01
x1.x3	0.02	x1.x3	0.02
x1.x4	0.05	x1.x4	0.02
x1.x5	0.01	x1.x5	0.01
x1.x6	0.01	x1.x6	0.01
x2.x3	0.05	x2.x3	0.08
x2.x4	4.87	x2.x4	3.20
x2.x5	0.51	x2.x5	0.88
x2.x6	0.39	x2.x6	0.21
x3.x4	1.69	x3.x4	1.03
x3.x5	0.18	x3.x5	0.34
x3.x6	0.16	x3.x6	0.09
x4.x5	0.58	x4.x5	0.90
x4.x6	0.29	x4.x6	0.13
x5.x6	0.82	x5.x6	0.81

Table 5: Input parameter interaction effects for the 914.4mm and 610mm diameter pipelines (Table 4 shows the key for the variable names)

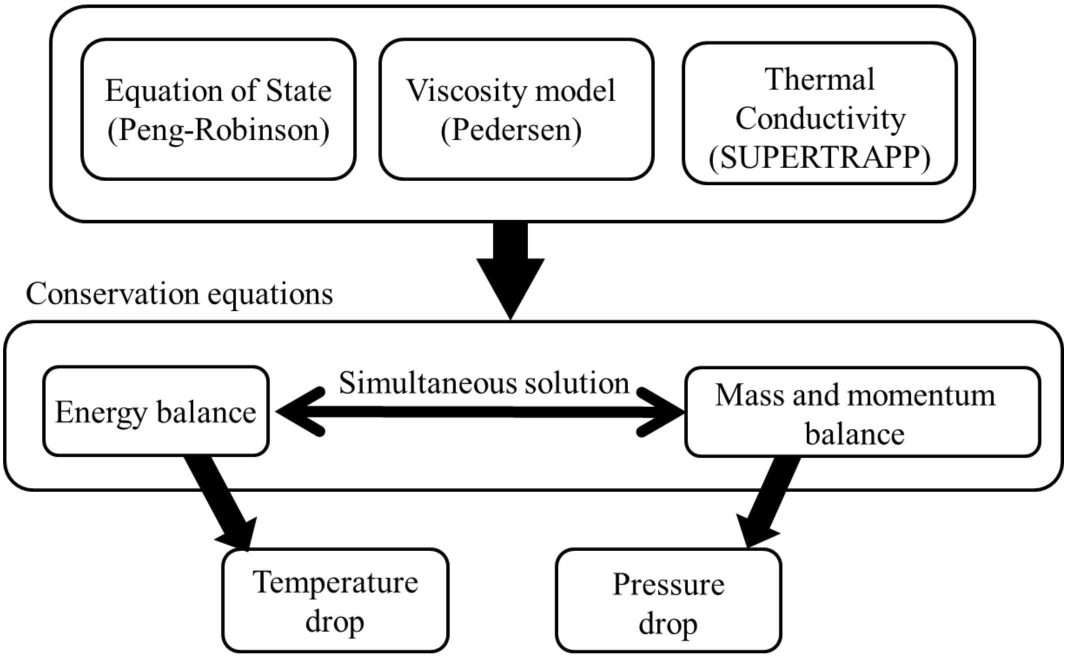


Figure 1: Flow diagram indicating the calculation methodology in the hydraulic analysis

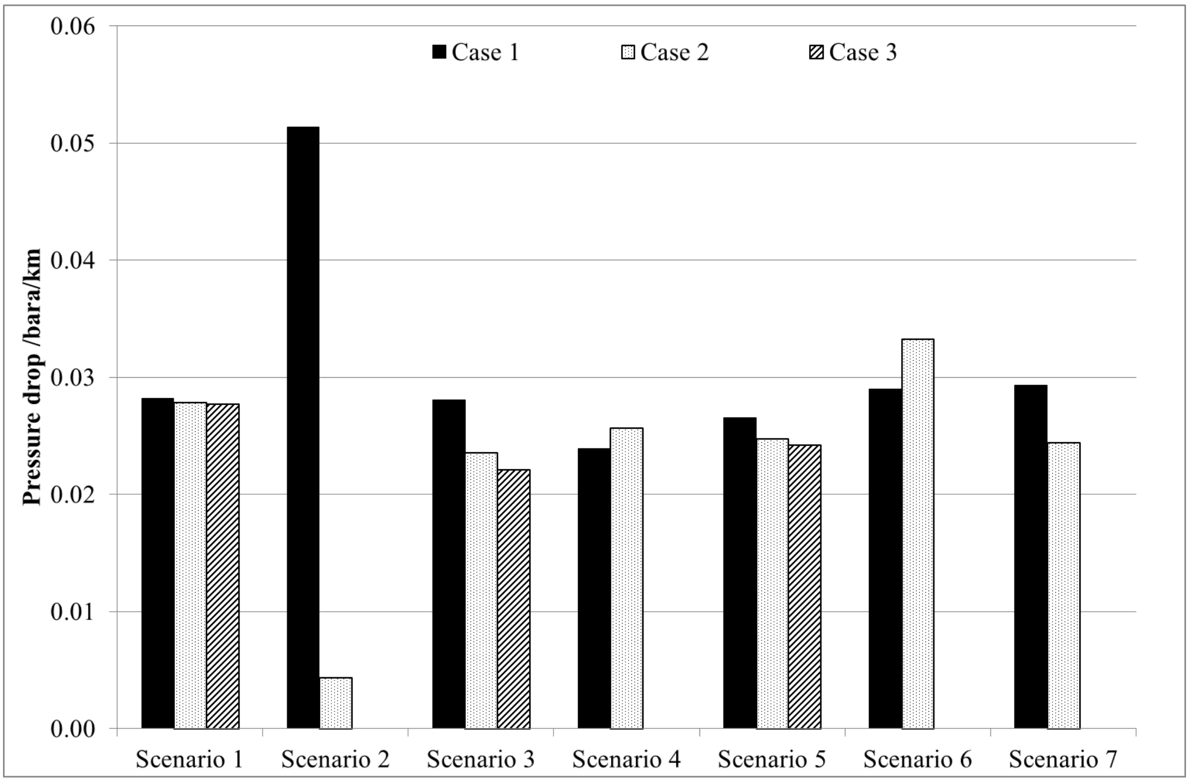


Figure 2: Pressure drop per kilometre of pipeline for the case studies used in the preliminary study

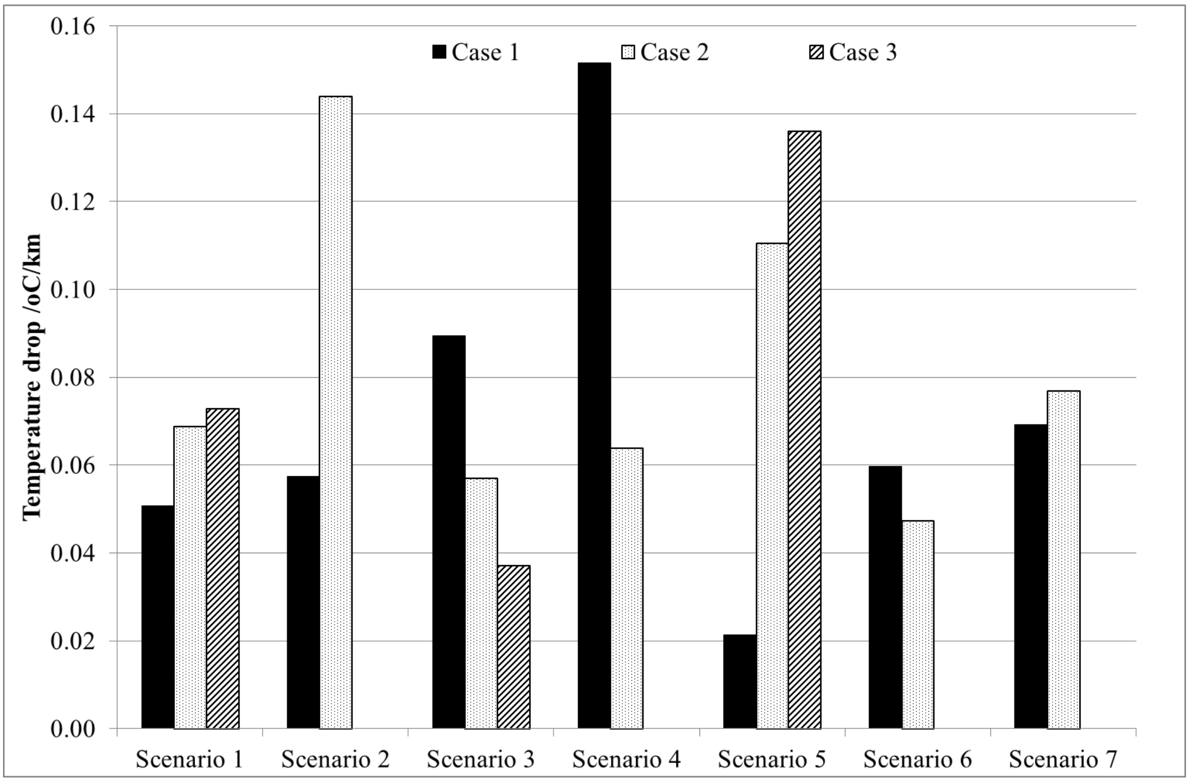


Figure 3: Temperature drop per kilometre of pipeline for the case studies used in the preliminary study

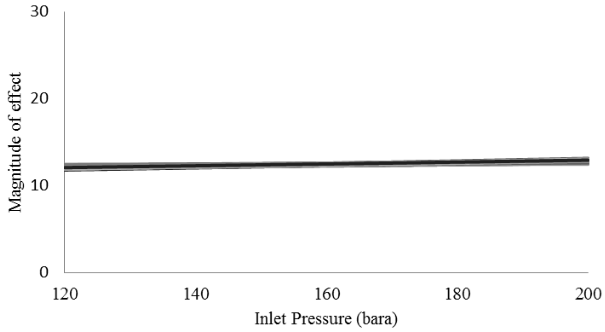


Figure 3a: Effect of Varying Inlet Pressure on Outlet Temperature

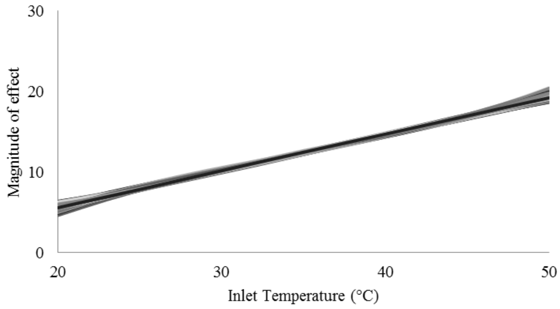


Figure 3b: Effect of Varying Inlet Temperature on Outlet Temperature

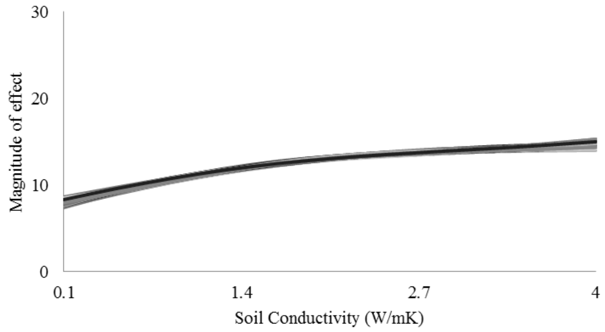


Figure 3c: Effect of Varying Soil Conductivity on Outlet Temperature

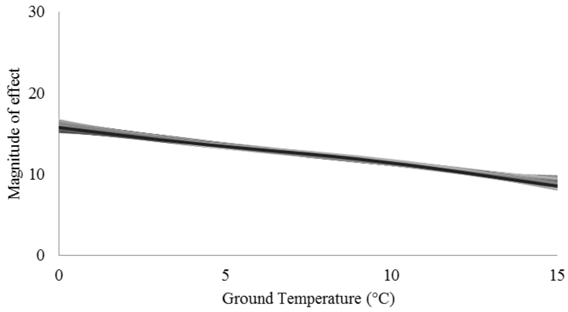


Figure 3d: Effect of Varying Ground Temperature on Outlet Temperature

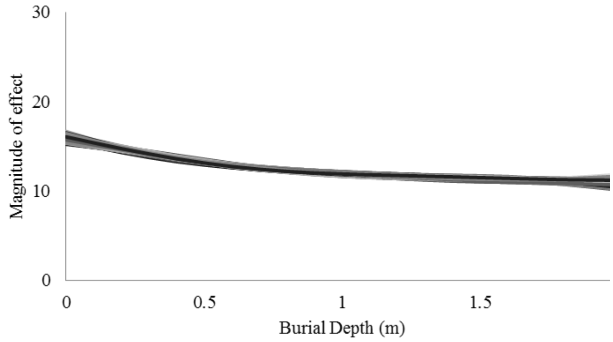


Figure 3e: Effect of Varying Burial Depth on Outlet Temperature

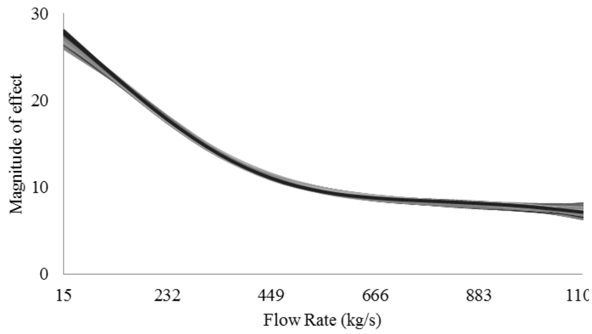
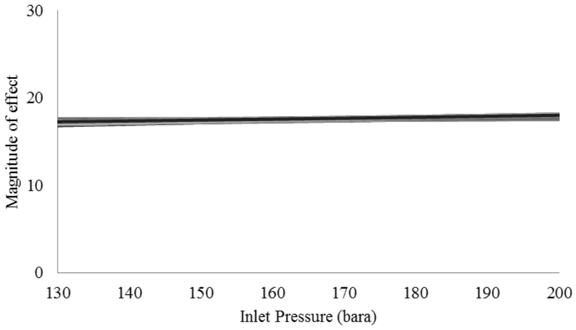


Figure 3f: Effect of Varying Flow Rate on Outlet Temperature

Figure 4: Effect of Study Parameters on Outlet Temperature for 914.4mm OD Pipeline



4a: Effect of Varying Inlet Pressure on Outlet Temperature

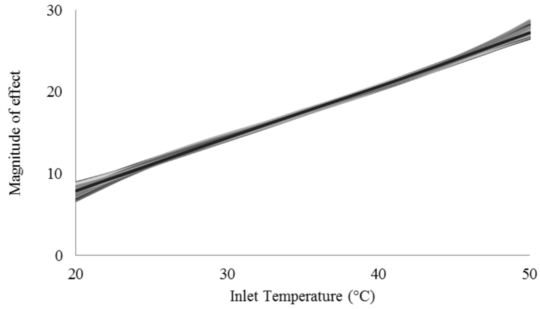


Figure 5b: Effect of Varying Inlet Temperature on Outlet Temperature

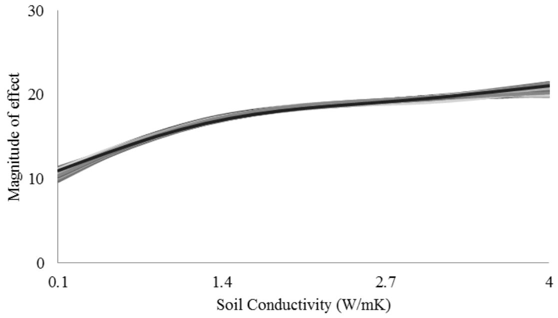


Figure 5c: Effect of Varying Soil Conductivity on Outlet Temperature

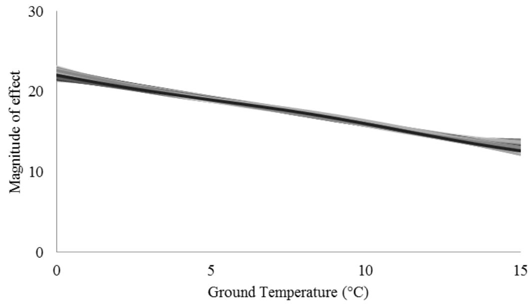


Figure 5d: Effect of Varying Ground Temperature on Outlet Temperature

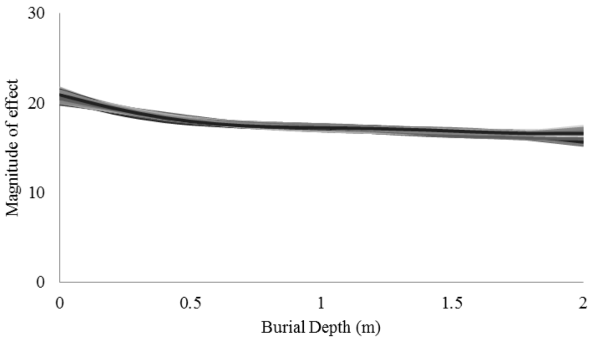


Figure 5e: Effect of Varying Burial Depth on Outlet Temperature

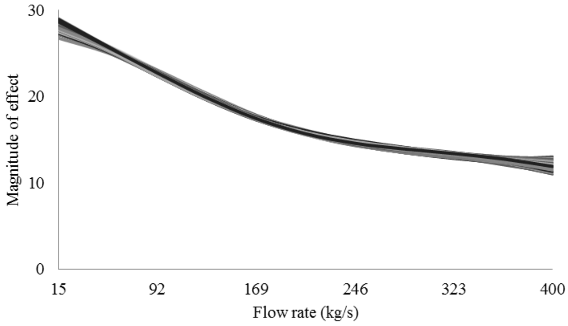


Figure 5f: Effect of Varying Flow Rate on Outlet Temperature

Figure 5: Effect of Study Parameters on Outlet Temperature for 610mm OD Pipeline